Data Fitting Aided Kramers–Kronig Receiver Using Artificial Neural Network

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***Abstract*—We propose and demonstrate the data fitting aided Kramers–Kronig receiver based on the artificial neural network, which is not only suitable for non-ideal square-law detection, but also supports accurate field reconstruction without DC recovery when using AC-coupled photodetectors.**

Keywords—artificial neural network, fitting, single sideband, direct-detection, Kramers–Kronig receiver, DC recovery.

I. INTRODUCTION

The Kramers–Kronig (KK) receiver, which can enable vector field reconstruction based on one single-ended photodetector (PD) in direct-detection systems, has been attracted extensive attentions in recent years [1-6]. Since the phase information of vector field is extracted from the amplitude information of minimum phase signal (MPS) via Hilbert transformation [1], thus whether accurate amplitude of MPS can be obtained is a vital point that determines the performance of the KK receiver [2]. However, the following two scenarios may inevitably affect the acquired amplitude of MPS in practical systems. First of all, DC blocking operation at the receiving end (which is quite preferable for high-speed direct-detection systems) will seriously distort the desired amplitude. Many solutions have proposed to recover the lost DC component. They can be mainly divided into two different categories, one is guess-and-check approach [1, 4], and the other is employing zero-padded preambles [5, 6]. Nevertheless, the former needs to calculate the target result such as bit error ratio (BER) for each estimated DC value case, and an optimal performance can be only obtained by multiple iterative estimated operations, resulting in a complicated DSP procedure as well as high power consumption. Whereas the latter requires a different signal transmission format from conventional, which hinders the scalability and wide applicability of the system. On the other hand, the factors such as imperfect design or the presence of power saturation at the receiver may cause the detection model to deviate from the traditional square-law characteristic. In this case, it is not accurate to obtain the amplitude of MPS from the detected current by simple square root operation. This is another important but overlooked issue which has undoubted impact on the performance of KK receiver.

In this paper, we propose the data fitting aided KK receiver. The conversion bridge between the output current of PD and the intensity of the MPS prior to PD is established through artificial neural network (ANN) fitting technique. Two different models including quadratic and polynomial characteristics are modeled for PD detection. Furthermore, we also consider DC-coupled and AC-coupled PD scenarios. The proposed scheme is verified by the simulation on 46 Gbps 16QAM signal with 80km optical fiber transmission. Results show that the ANN fitting can help KK receiver improve the receiving sensitivity of imperfect square-law detection by 0.6 dB. More importantly, the proposed KK receiver based on ANN fitting achieves accurate field reconstruction without DC recovery when using AC-coupled PD.

II. SYSTEM SETUP

The simulation setup is shown in Fig.1. At the transmitter, rand bit sequence with the length of 2^{17} is mapped into 16QAM symbols. Then the single sideband (SSB) signal is generated via frequency shifting by half of the signal bandwidth after eight-fold upsample and pulse shaping. Using an IQ modulator (IQM) biasing above the null point to perform the electro-optic conversion. Adjusting the bias to ensure the power of optical carrier is larger than that of the sideband signal. Thus, an optical SSB signal termed as optical MPS can be obtained. After 80 km standard single mode fiber (SSMF) transmission, a variable optical attenuator (VOA) is used to sweep the received optical power (ROP). We adopt different detection models and whether to block the DC to model the PD. Among them, quadratic model represents the conventional square-law detection, while the polynomial model is employed to symbolize imperfect detection characteristic. Moreover, with and without DC blocking denote the DC-coupled PD and AC-coupled PD, respectively. The optical intensity of MPS is converted to current after optic-electric conversion. Subsequently, this current is fed to receiver DSP after analog-to-digital conversion (ADC). Then resampling, KK algorithm, electrical chromatic dispersion compensation (CDC), baseband recovery, matched filtering, RLS equalization, symbol demapping and BER calculation are performed in sequence.

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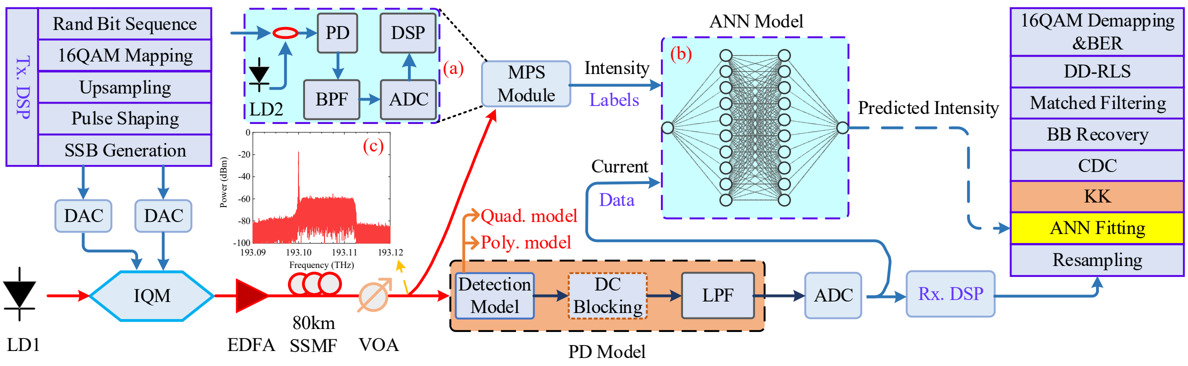

Fig. 1 The simulation setup for ANN fitting aided KK receiver with different PD models.

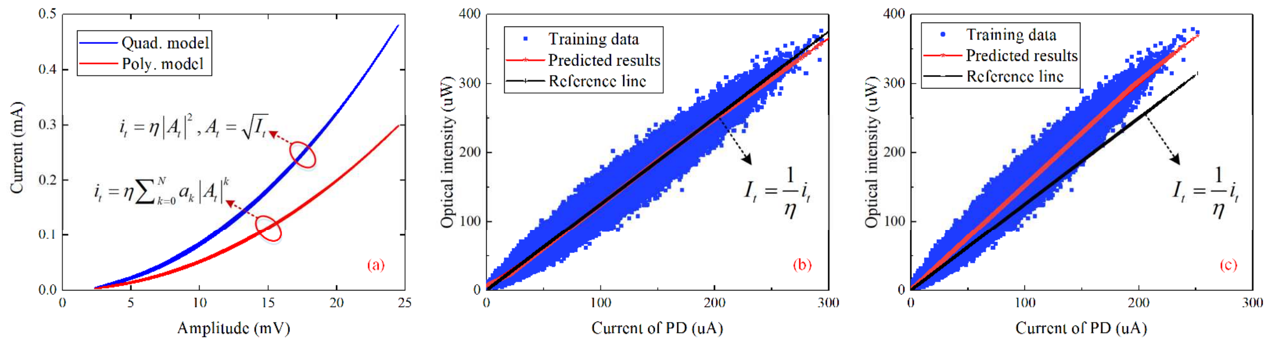

Fig. 2 (a) Detection curves with the responsivity η=0.8 for quadratic and polynomial models. ANN partial training data of offline training and predicted optical intensity of online testing for (b) quadratic detection model and (c) polynomial detection model.

In order to obtain accurate MPS intensity for KK module from the detected current under different PD models, the ANN fitting model shown in Fig. 1 (b) is employed. It consists of a four-layer network with the number of neurons (1, 10, 10, 1). Rectified linear unit is selected as the activation function of hidden layers, while without using any activation function for the input and output layers. The overall fitting process contains offline training and online testing two steps. In offline training, the intensity of optical MPS before PD and the detected current after PD are fed to the ANN model regarded as labels and training data, respectively.

By the way, an additional link module termed as MPS module is used to obtain the intensity of optical MPS. The detailed structure of this module is shown in Fig. 1 (a). It contains one laser, one optical coupler, one PD, one electrical band-pass filter (BPF), one ADC and the corresponding DSP processing. The target optical MPS after optical fiber transmission (as shown in Fig. 1 (c)) is first coupled with an optical carrier. The frequency interval between the added optical carrier and original optical MPS is 15 GHz. After optical heterodyne detection via the PD, the target optical MPS is converted into an intermediate frequency (IF) signal with a center frequency of about 15 GHz. Then a BPF is used to extract the IF signal. The obtain IF signal is fed to a DSP for intensity calculation by taking the modulo and squaring operation. When the PD used in MPS module has a relatively ideal response, whether it is AC- or DC-coupling, the conversion from optical MPS to electric IF signal can be regarded as a linear mapping process. Therefore, the measured intensity information is proportional to the intensity of target optical MPS. It should be noted that, this extra MPS module is only needed during the offline training step, it can be removed at the online testing stage once the required ANN fitting model has been established. Therefore, the additional MPS module will not bring too much complexity to the system.

For the sake of objectivity of the fitting model, the random bit sequence is used at the transmitter. The whole data mapped from 2^{19} random bits (consists of four frames, 4×2^{17}) are divided into training set and test set with the ratio of 75:25. The weights of ANN model are only updated by the training set, and meanwhile the max-norm weight constraint is used to prevent overfitting. In addition, the loss function is mean squared error (MSE) which is a loss function often used for fitting. In online testing, we obtain the predicted intensity of optical MPS by feeding the measured current to established ANN fitting model. After that, the accurate amplitude of MPS is obtainable from its intensity by the built-in square root operation of KK module.

III. Results And Discussion

Fig. 2 (a) shows the detection curves with a responsivity η=0.8 for quadratic and polynomial models. The former approximates the square law curve while the latter has some deviation. Their corresponding results when using ANN fitting model are shown in Fig. 2 (b) and (c). The blue scatter points represent the partial training data during off-line training and the red line is the predicted optical intensity mapped from the detected current after online testing. Meanwhile, the linear curve of optical intensity and current is also given as reference. It can be found that the predicted intensity curves of the two detection models are both located in the center of the massive scatter points. This implies that the selected ANN model has achieved the expected fitting effect.

For the conventional quadratic detection model without ANN fitting, the BER performance comparison with and without KK is shown in Fig. 3 (a). It can be seen that the effect

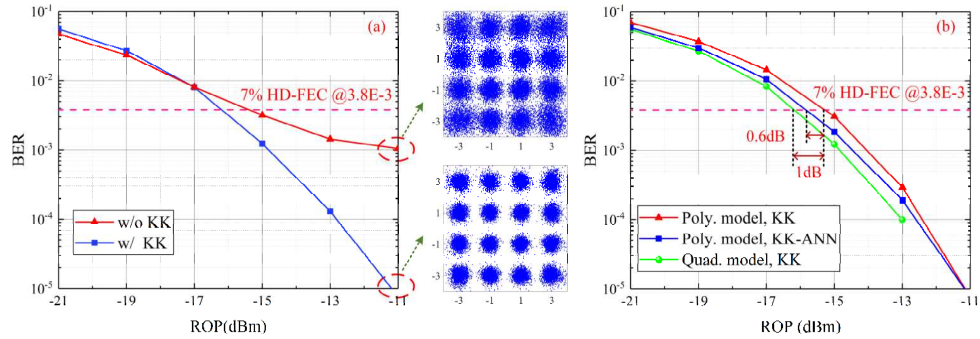

Fig. 3 (a) BER performance comparison with and without KK under quadratic model. Insets show the constellation diagrams of 11.5Gbd 16QAM signal at the fixed ROP of -11dBm, respectively. (b) BER performance comparison between the two detection models.

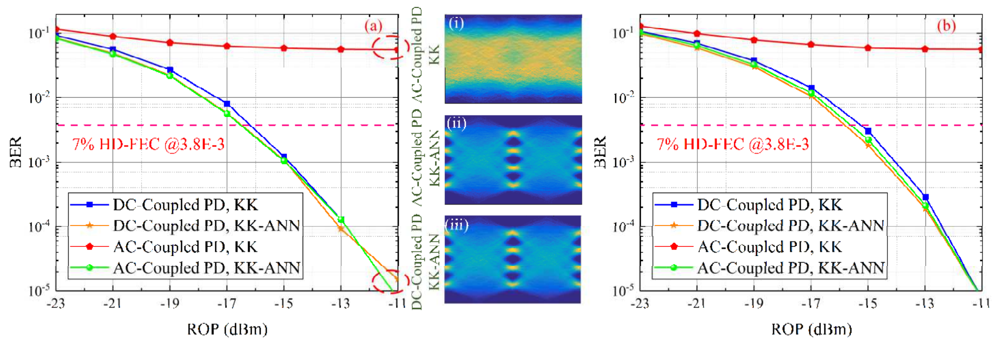

Fig. 4 BER performance comparison with DC-Coupled or AC-Coupled PDs under (a) quadratic model and (b) polynomial model. Insets (i)-(iii) show the corresponding eye diagrams of 11.5Gbd 16QAM signal at the fixed ROP of -11dBm for quadratic model.

of KK scheme becomes more pronounced with the increase of ROP. Especially, using KK processing can improve the BER by about two orders of magnitude at the fixed ROP of -11 dBm. This mainly benefits from the cancellation of signal-to-signal beating interference [4]. The insets show their corresponding constellations of 11.5 Gbd 16QAM signal. An appreciable performance improvement can also be observed. Fig. 3 (b) further compares the BER performance between the quadratic and polynomial models. Considering the HD-FEC threshold (3.8×10^{-3}), the ROP sensitivity of the later is inferior to the former by approximately 1 dB at the case of only using KK processing. This mainly because the detected current via the polynomial model cannot accurately represent the MPS's intensity, resulting in a deviation in the amplitude calculated via the square root operation. Nevertheless, after more accurate intensity is obtained through ANN fitting, the ROP sensitivity could be improved by about 0.6 dB as compared with the original KK scheme.

The influences of DC component on BER performance under quadratic model and polynomial model are shown in Fig. 4 (a) and (b). Similar behavior can be found from the two different detection models. For the DC-coupled PD case, the DC component preserves in DSP, hence BER performance of KK receiver is almost the same whether ANN fitting is used or not. However, for the AC-coupled PD, the DC component has been lost after detection. This means the intensity of MPS feeding to KK module is incorrect, thus leading in an intolerable BER. Instead, after obtaining accurate intensity of MPS from the blocked current through ANN fitting, AC-coupled PD can also achieve the same BER performance as DC-coupled PD. It should be emphasized that in this case, we have not performing DC recovery based on the detected current like the traditional method [6]. Insets (i)-(iii) show the eye diagrams of 11.5 Gbd 16QAM signal at the ROP of -11 dBm under quadratic model for AC-coupled PD without and with ANN, as well as DC-coupled PD with ANN, respectively. Among them, the latter two schemes exhibit similar performance, which is noticeably superior to the former.

IV. Conclusions

In conclusion, the ANN fitting aided KK receiver has been proposed and demonstrated by simulation. The quadratic and polynomial models are used to characterize the detection effects of conventional and imperfect receivers, respectively. Additionally, the impact of DC component is also considered by means of DC-coupled or AC-coupled PDs. The results show that the proposed ANN fitting aided KK receiver can not only improve the performance of imperfect receiver by about 0.6 dB, but also achieves accurate field reconstruction without DC recovery when using AC-coupled PD.

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